Study of Three-Nucleon Dynamics in the dp breakup collisions using the WASA detector at COSY-Jülich

Barbara Kłos for Wasa-at-Cosy Collaboration
Institute of Physics, University of Silesia

The 25th European Conference on Few Body Problems in Physics, Mainz 2023

Motivation for studies of d+p → p+p+n

- Theoretical calculations in relativistic approach with three nucleon force (3NF) included are available

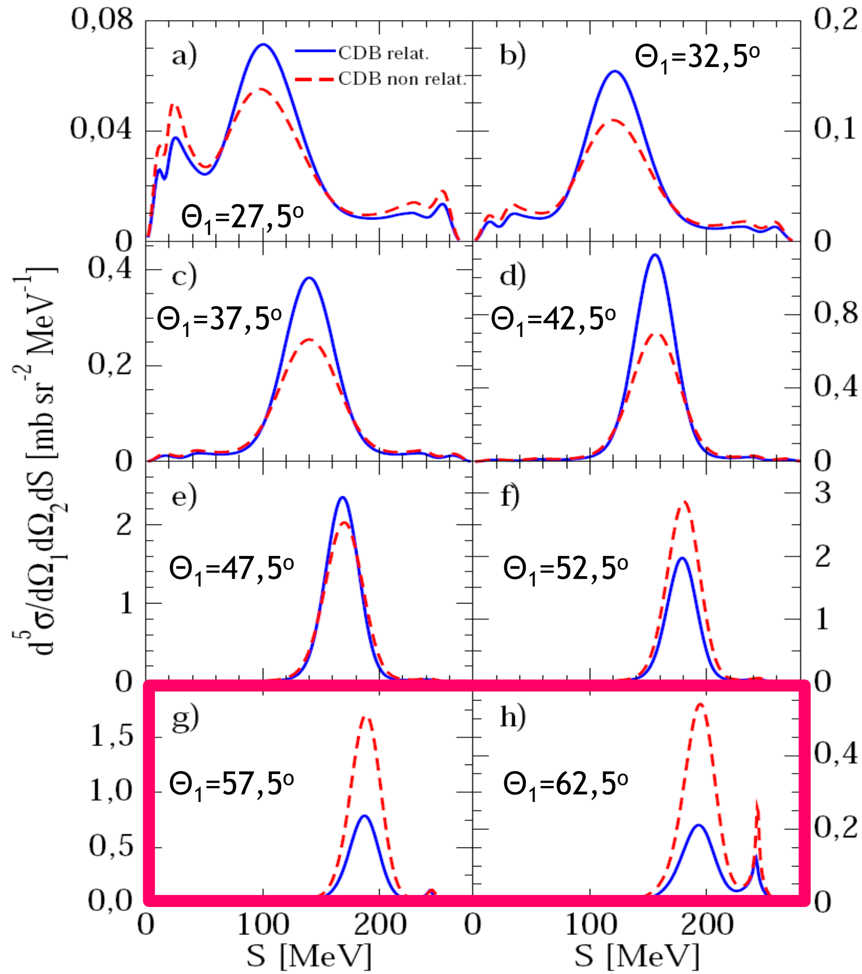
- Investigations at relatively high energies are important to confirm theoretical predictions for relativistic effects and to unambiguously fix a relevance of the 3NF.

- Cross sections for the deuteron breakup in d+p system at medium and higher energy region are expected to be very sensitive to relativistic and three nucleon force effects.

Relativistic Effects in the Cross Section

R. Skibiński, Eur. Phys. J. A 30, 369, (2006)

first calculations available for
N+d breakup @ **200 MeV**



$\theta_2=37.5^0, \ \varphi_{12}=180^0$

very strong effects,
(dynamical & kinematical)
even up to 60% !!

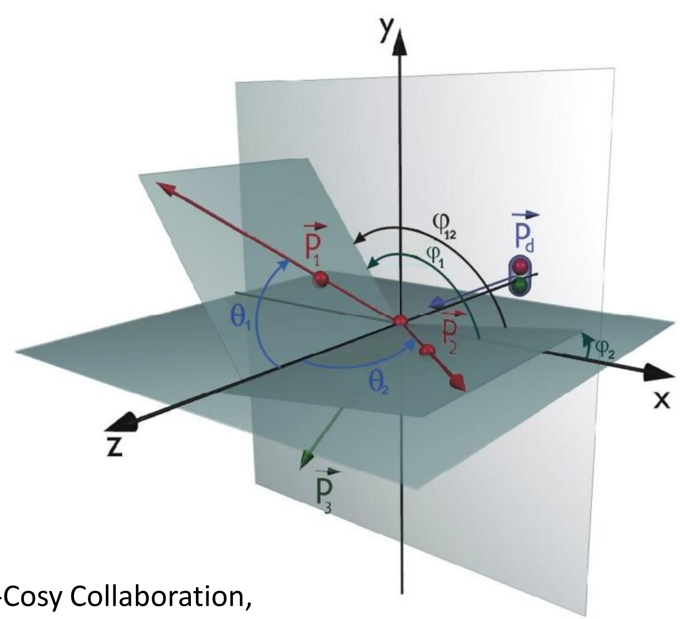
Barbara Kłos for Wasa-at-Cosy Collaboration,
University of Silesia

Breakup Reaction Kinematics
$d+p \longrightarrow p+p+n$

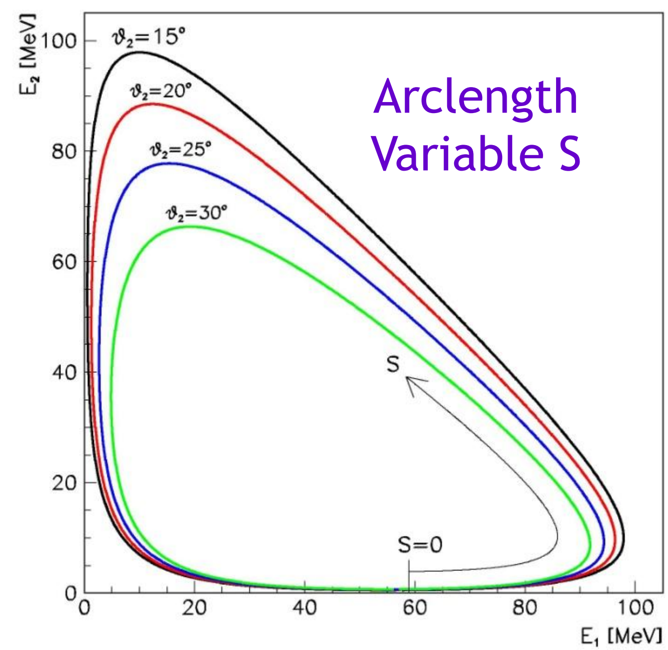
- Three nucleons in the final state - 9 variables
- Energy-momentum conservation – 4 equations

➢ Five independent kinematical variables
  - ✓ Complete (exclusive) exp. – measured ≥ 5
  - ✓ Inclusive exp. – measured ≤ 4 parameters

$^{1}H(d,pp)n$
measured:
directions and energies of two protons, i.e.
θ_1, φ_1, E_1
θ_2, φ_2, E_2



$\Theta_1=15^o,\ \varphi_{12}=90^o$



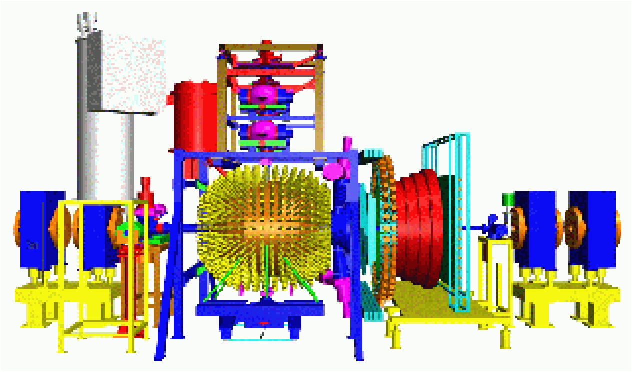
Barbara Kłos for Wasa-at-Cosy Collaboration,
University of Silesia

Experiment WASA 214

p(d,pp)n measurement **@ WASA detector**

WASA (Wide Angular Shower Apparatus)

at COSY, FZ-Jülich (Germany)



Experimental conditions:

* unpolarized deuterons
* energies of 340, 380, 400 MeV in supercycle mode, 300 MeV separetely
* pellet H_2 target
* determination of energies and emission angles of both protons
* simultaneous measurement of the d-p elastic scattering channel
  - absolute cross section normalization
  - geometry checks

Barbara Kłos for Wasa-at-Cosy Collaboration,
University of Silesia

Experimental setup

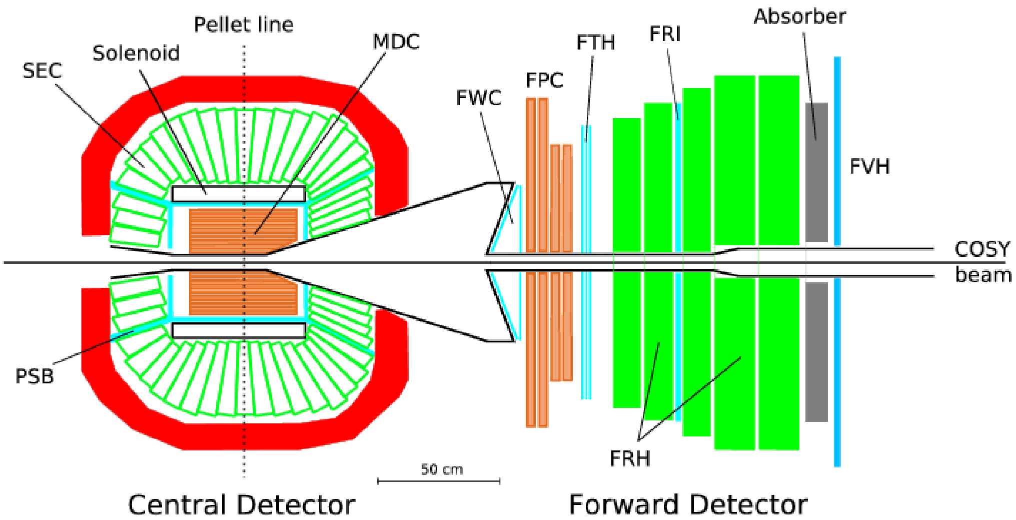
Pellet target system: protons, deuterons

Pellet diameter: 25-35 μm

Rate in beam: 5-6 kHz

Effective target density: 10^{15} cm^{-2}

Beam diameter:2-4 mm



Schematic view of the detection system

Central Detector

Angular acceptance 20°-169°

Neutral and charged particles

Energies γ up to 800MeV

Energy resolution: ~8%

Momenta of electrons 20-600MeV/c

Energy resolution: ~2%

Momenta of protons 200-800MeV/c

Energy resolution: ~6%

Forward Detector

Angular acceptance 3°-18°

Angle resolution 0.2°

Maximum kinetic energy: protons (300MeV), deuterons(400MeV)

Energy resolution:3-8%

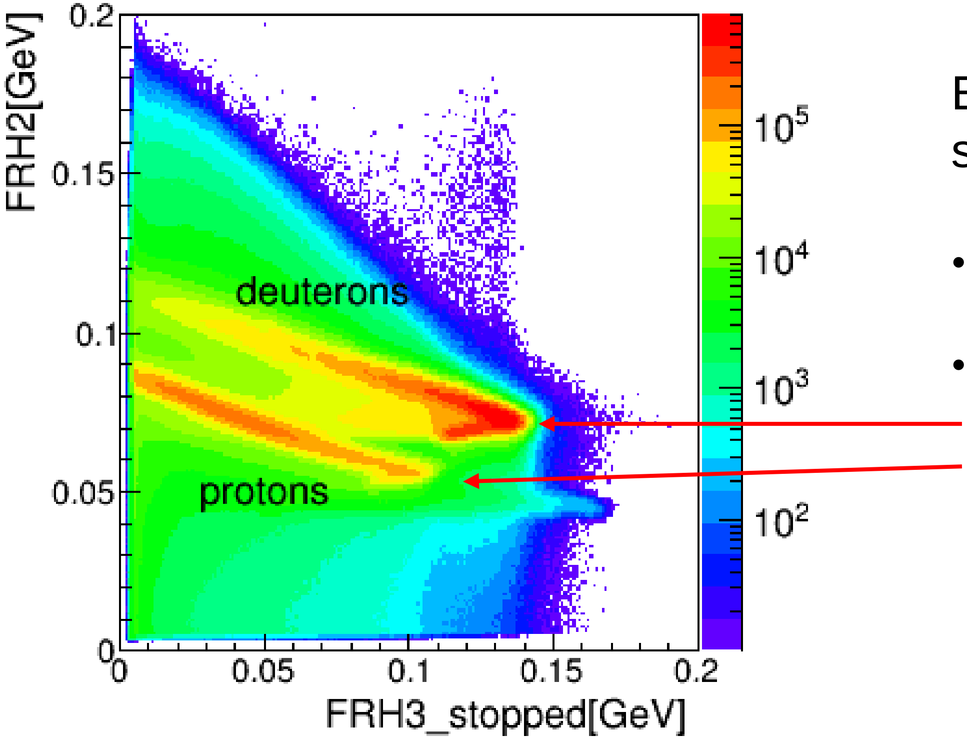
Particle identification ΔE-E

Barbara Kłos for Wasa-at-Cosy Collaboration,
University of Silesia

Data Analysis

Event Selection and Particle Identification

in the Forward Detector

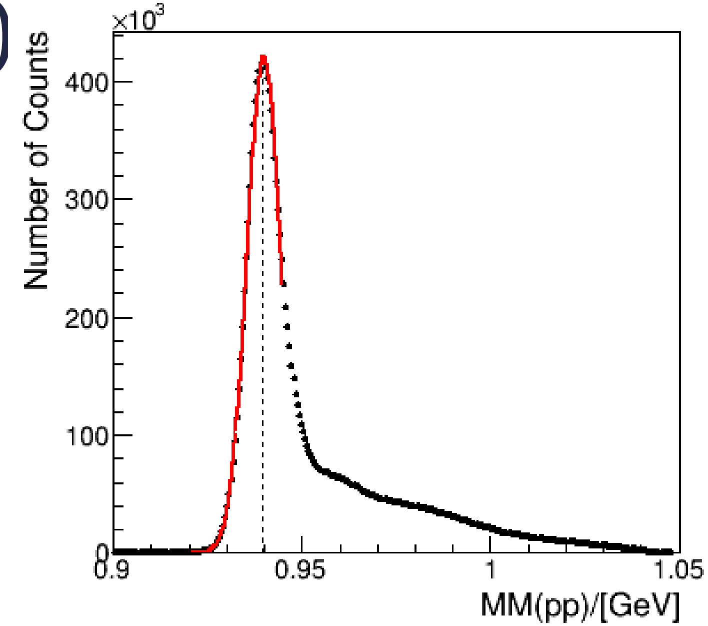


Example of the ΔE-E identification spectrum in the Forward Detector.

- condition: track finished in the FRH3 layer (no signal in the FRH4 layer);
- punch-through corresponds to particles stopped in the additional material layer between FRH3 and FRH4; energy has to be corrected.

Barbara Kłos for Wasa-at-Cosy Collaboration,
University of Silesia

Data Analysis (340 MeV)



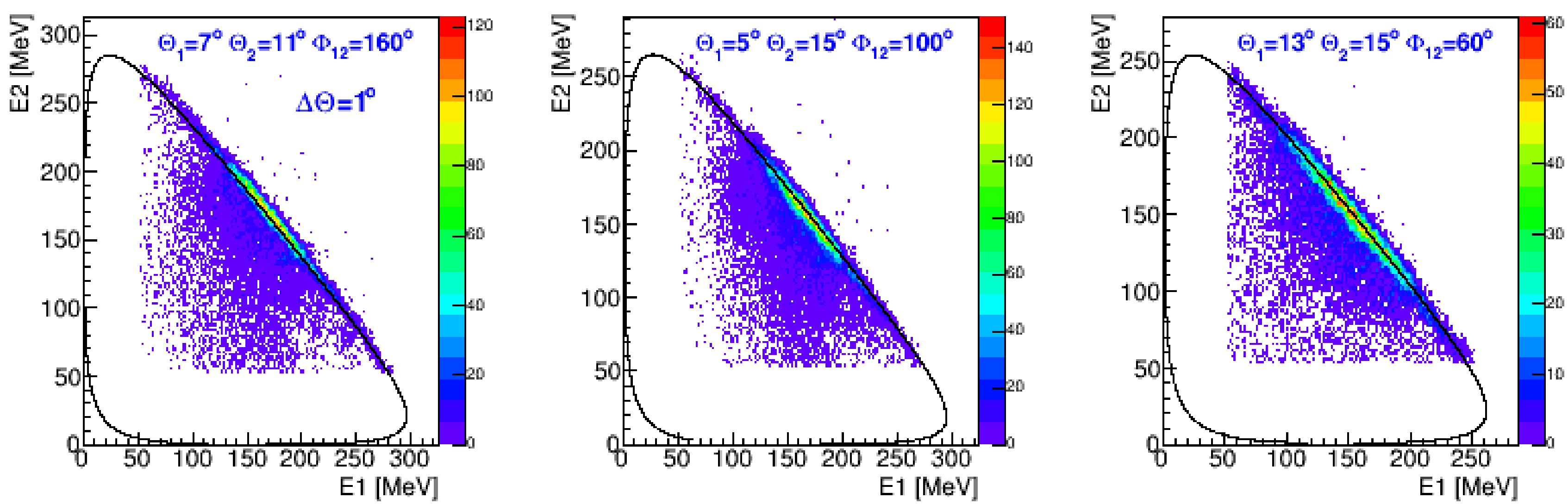
Missing mass

$$MM = \sqrt{(E_{in} - E_{p1} - E_{p2})^2 - (P_{in} - P_{p1} - P_{p2})^2}$$

c=1

Breakup Reaction Kinematics

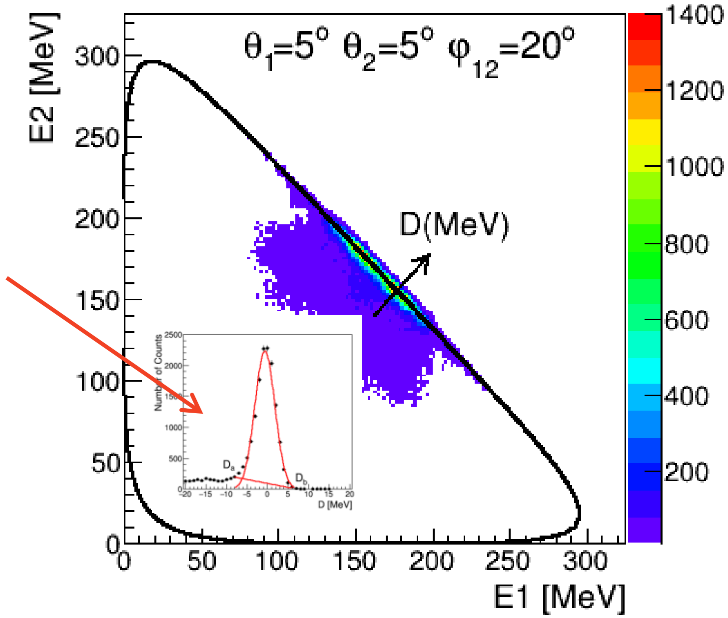
d+p → p + p + n

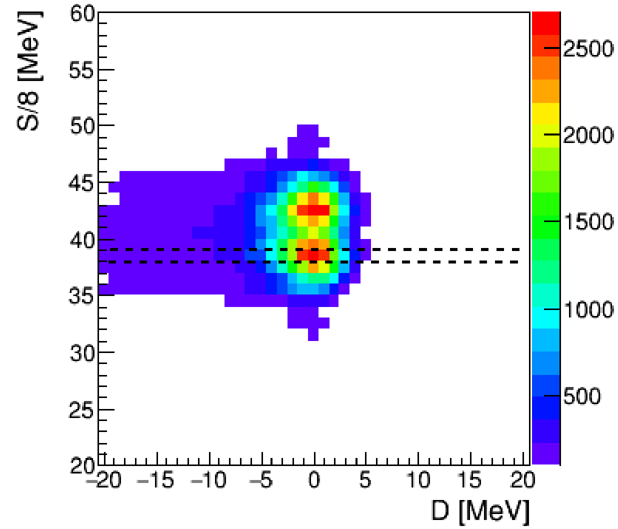


Data Analysis (340 MeV)

Selection of events and background subtraction

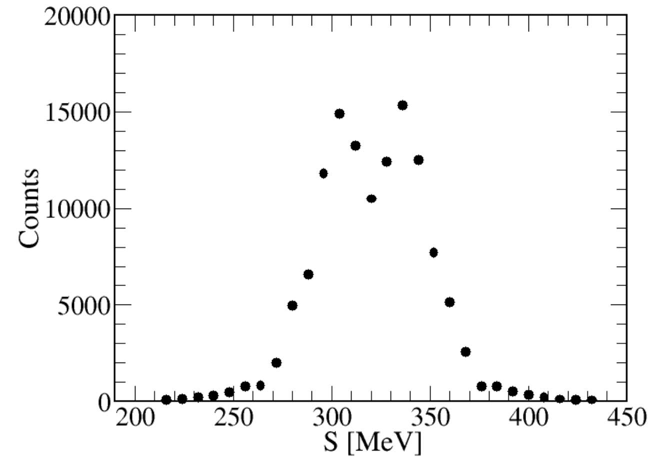
low background





Transformation of E_2 vs E_1 spectrum to S (arclength) vs D (distance from kinematics)

The E_2-E_1 coincidence spectrum of the two protons registred in one chosen kinematical configuration.
The solid line shows a three-body kinematical curve, calculated for the central values of the experimental angular ranges.

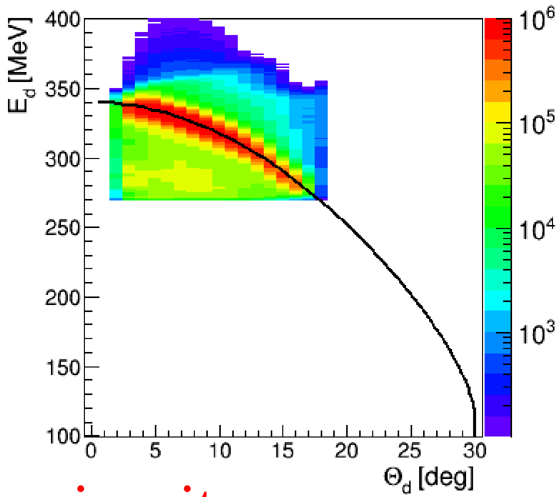


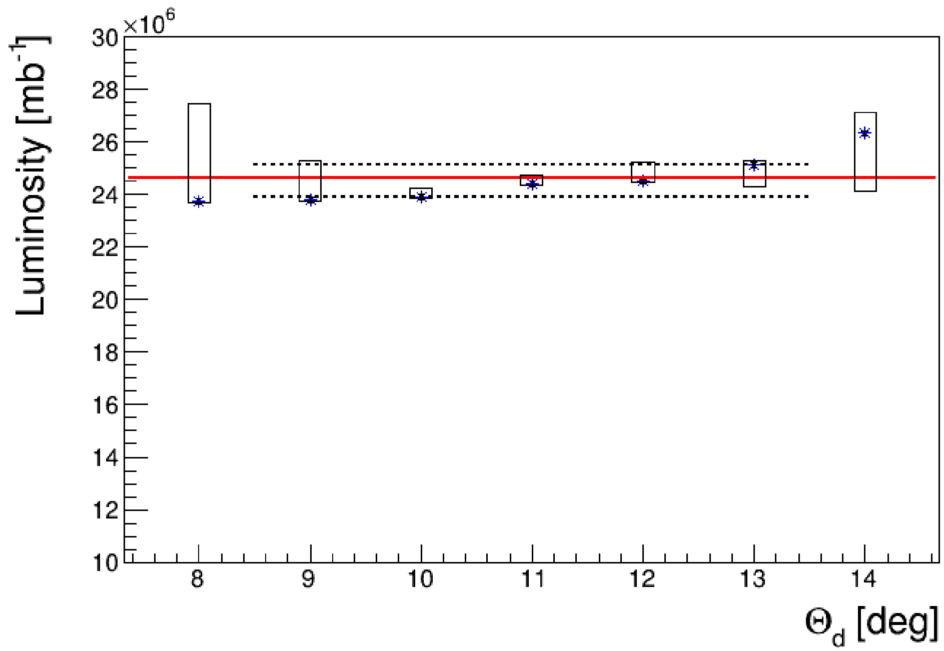
An example of S distribution of the rate of breakup events obtained for the chosen kinematical configuration

Barbara Kłos for Wasa-at-Cosy Collaboration,
University of Silesia

Data Analysis (340 MeV)

Selection of deuterons registered in FD; Luminosity





Luminosity

$$L = \frac{N_{el}(\theta_d)}{\sigma^{el}_{LAB}(\theta_d)\Delta\Omega_d \epsilon^{el}(\theta_d)}$$

N_{el} – number of elast. scatt. deuterons

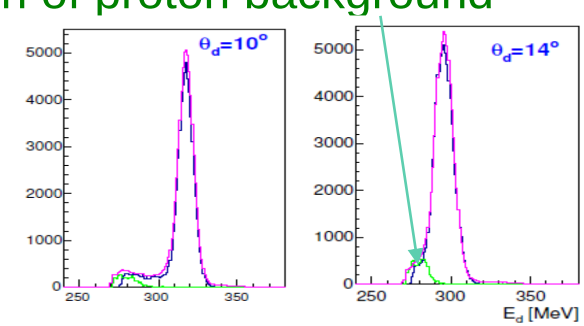
$\sigma^{el}_{LAB}(\theta_d)$ - elast. scatt. cross section

$\Delta\Omega_d = 2\pi\Delta\theta_d \sin\theta_d$ - solid angle

$\epsilon^{el}(\theta_d)$ - efficiency of deuteron detection (~80%)

Sources of systematic uncertainty:

- spread of data used for normalization
- contribution of proton background



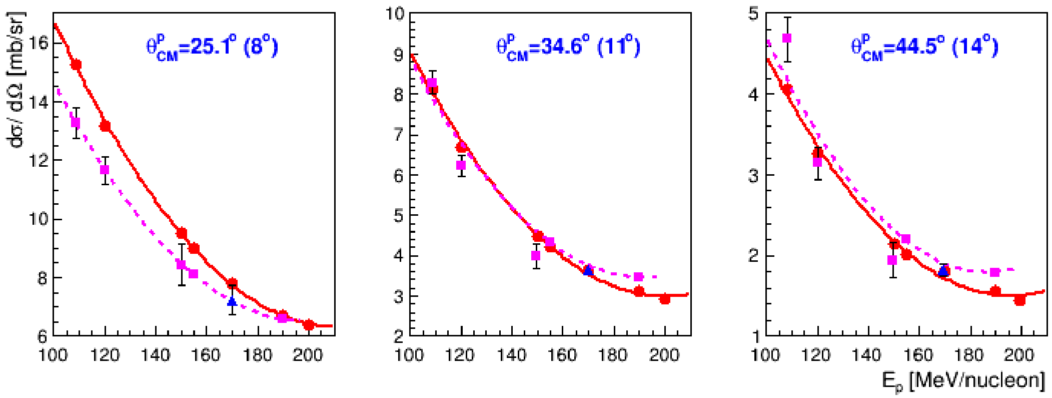
Barbara Kłos for Wasa-at-Cosy Collaboration,
University of Silesia

Data Analysis (340 MeV)

Luminosity, reference cross section $\sigma^{el}_{LAB}(\theta_d)$ for elastic scattering

1. exp. data (K. Ermisch *et al.*, Phys. Rev. C **68**, 051001(R) (2003).), irregularities
2. comparison of experimental data with theoretical calculation (data sets between 108 and 200 MeV): scatter and deficiency of calculations at the cross section minimum

Dependence of cross section on beam energy at each polar angle (out of minimum) was studied



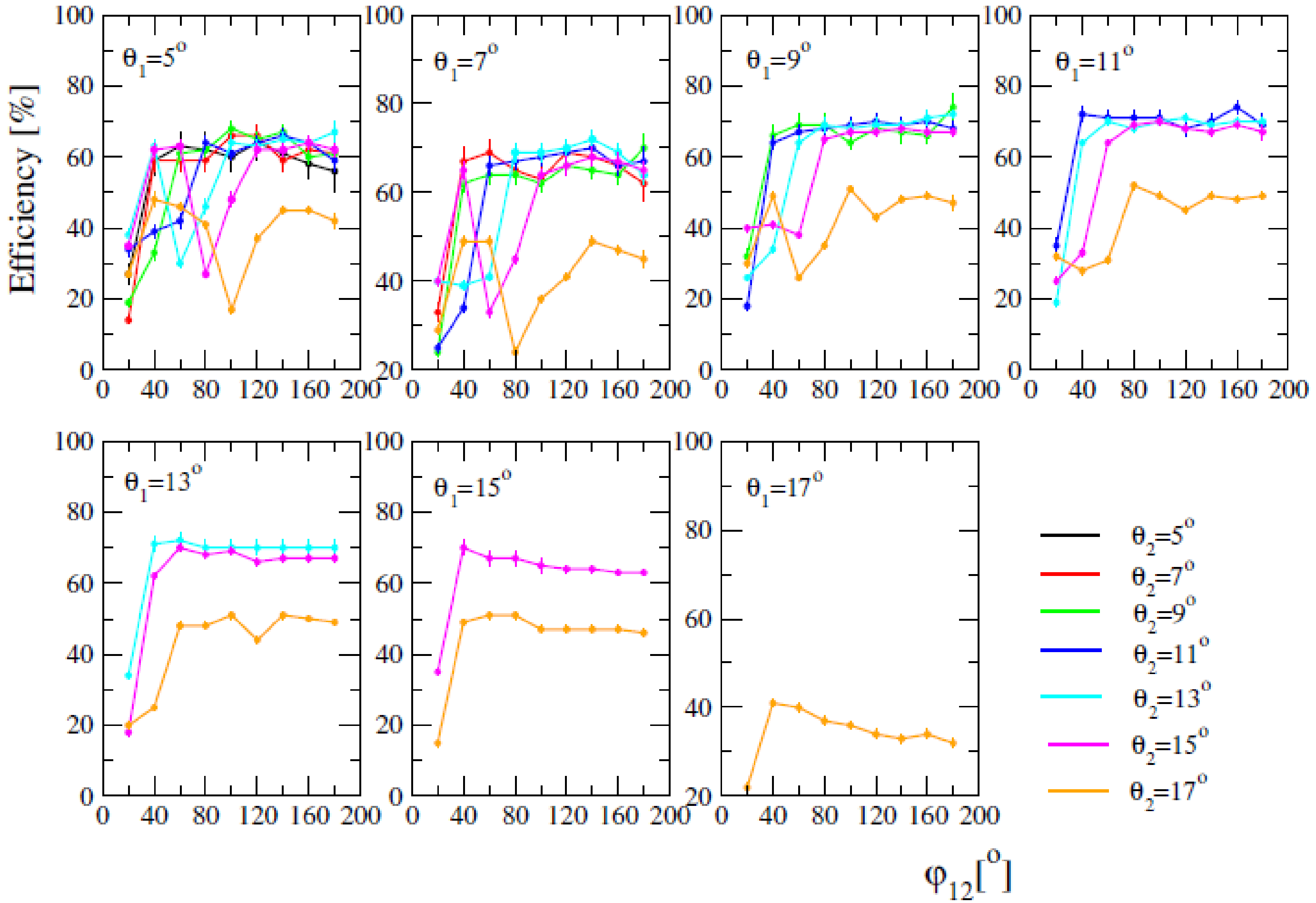
Experimental and theoretical energy dependence of the elastic scattering cross section a given Θ^p_{CM} angle in the CM system in a function of incident beam energy . The solid and dashed lines present functions fitted to points obtained from theoretical calculations and the data, respectively. Triangle and squares were determined from pd elastic scattering experiments.

the cross section $\sigma^{el}_{LAB}(\theta_d)$

1. Calculations
2. Measurement at 170 MeV
3. Polynomial fit to other data sets

Data Analysis (340 MeV)

Efficiency of the detection system for proton-proton coincidences obtained for each kinematical configuration ($\theta_1, \theta_2, \varphi_{12}$) using MC simulation.



Barbara Kłos for Wasa-at-Cosy Collaboration,
University of Silesia

Data Analysis (340 MeV)

Differential cross sections (189 configurations ≡ 5600 data points)
θ_1 and θ_2 in the range (5^o,15^o) with the step 2^o i φ_{12} (20^o,180^o) with the step 20^o

$$\frac{d^5\sigma(S,\Omega_1,\Omega_2)}{d\Omega_1 d\Omega_2 dS} = \frac{N_{br}(S,\Omega_1,\Omega_2)}{L\,\Delta\Omega_1\Delta\Omega_2\Delta S\epsilon^{br}(S,\Omega_1,\Omega_2)}$$

N_{br} number of breakup coincidences registred at the angles Ω_1, Ω_2 and projected onto a ΔS-wide arclength bin,

$\Delta\Omega_i$ solid angle,

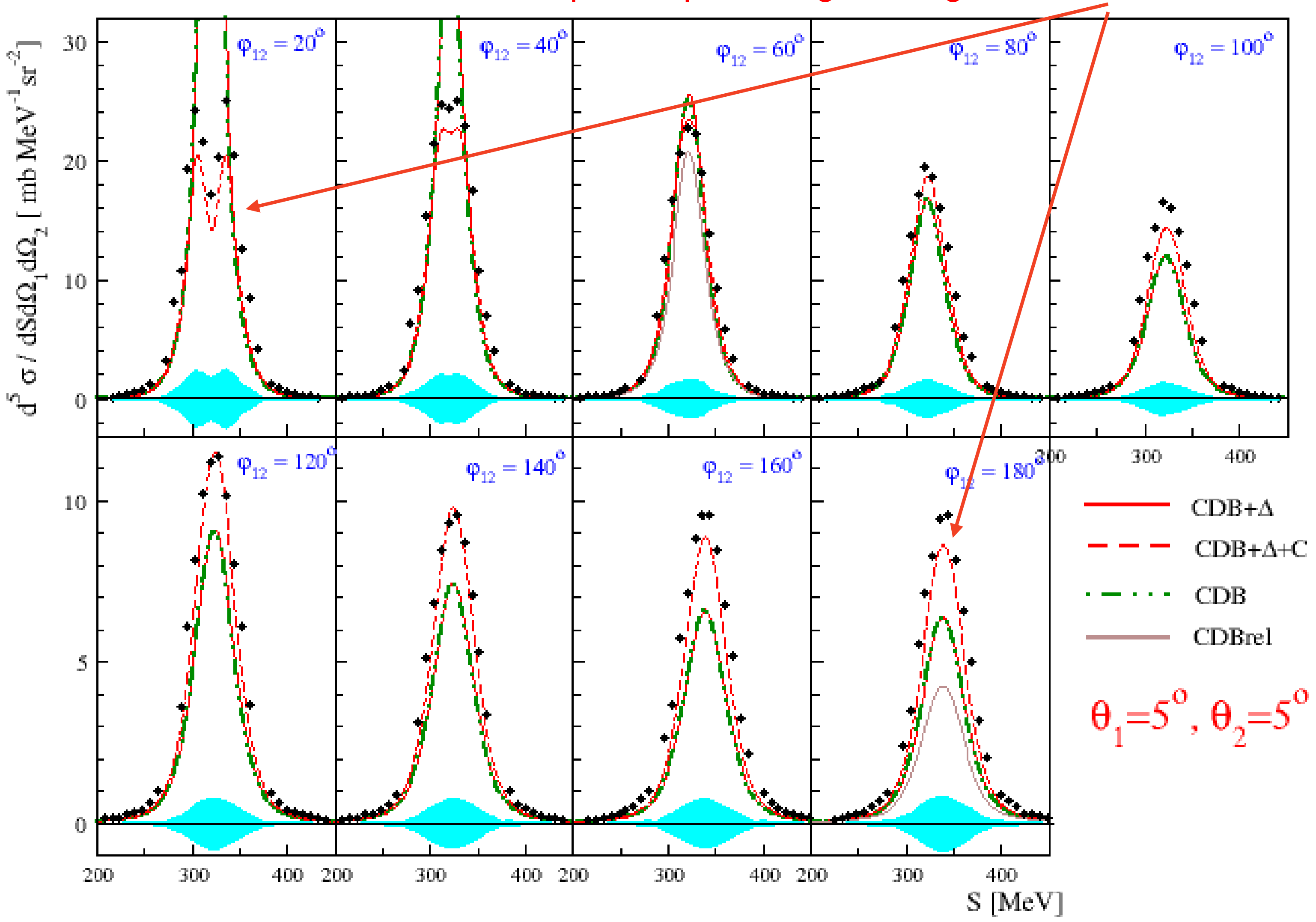
L luminosity,

ε^{br} efficiencies determined for each angular configuration.

Barbara Kłos for Wasa-at-Cosy Collaboration,
University of Silesia

Differential cross section

– data set for one combination of proton polar angles; large Coulomb effects observed



Barbara Kłos for Wasa-at-Cosy Collaboration,
University of Silesia

χ^2 Analysis (340 MeV)

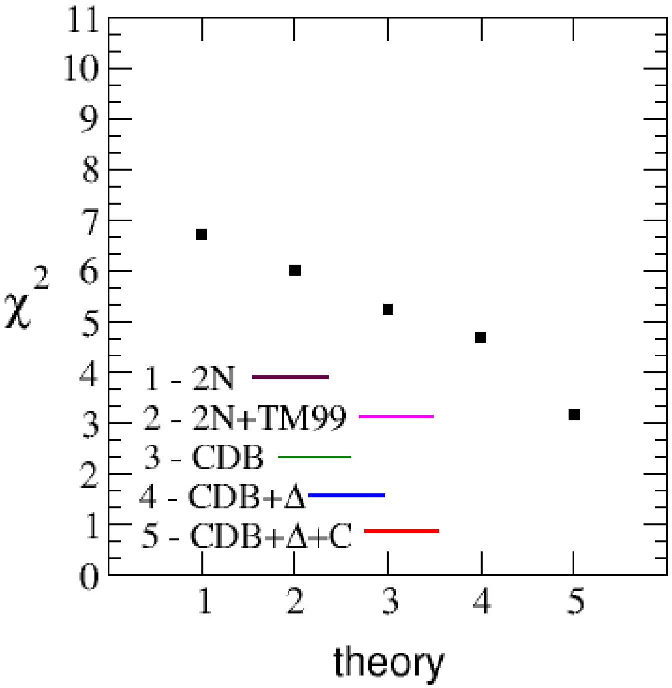
$$\chi^2 = \frac{1}{n_{d.o.f.}} \sum \frac{(\sigma_{theo}(\xi) - \sigma_{\exp}(\xi))^2}{(\Delta\sigma_{stat}(\xi) + \Delta\sigma_{sys}(\xi))^2}$$

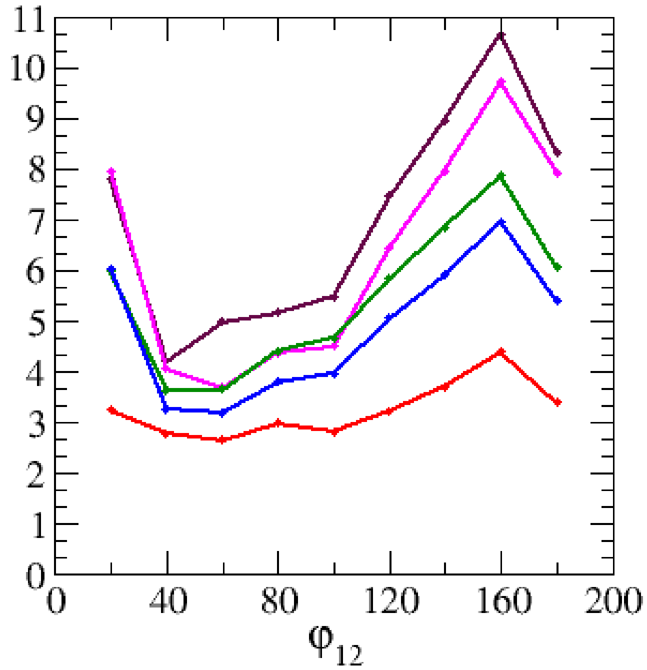
$\zeta = (\theta_1, \theta_2, \varphi_{12}, S)$ set of kinematic variables

$\Delta\sigma_{stat}, \Delta\sigma_{sys}$ statistical and systematical uncertainties

$\sigma_{\exp}, \sigma_{theo}$ cross section data and various calculations

$n_{d.o.f}$ number of data points





Coulomb Effects are important

Barbara Kłos for Wasa-at-Cosy Collaboration,
University of Silesia

χ^2 Analysis (340 MeV)

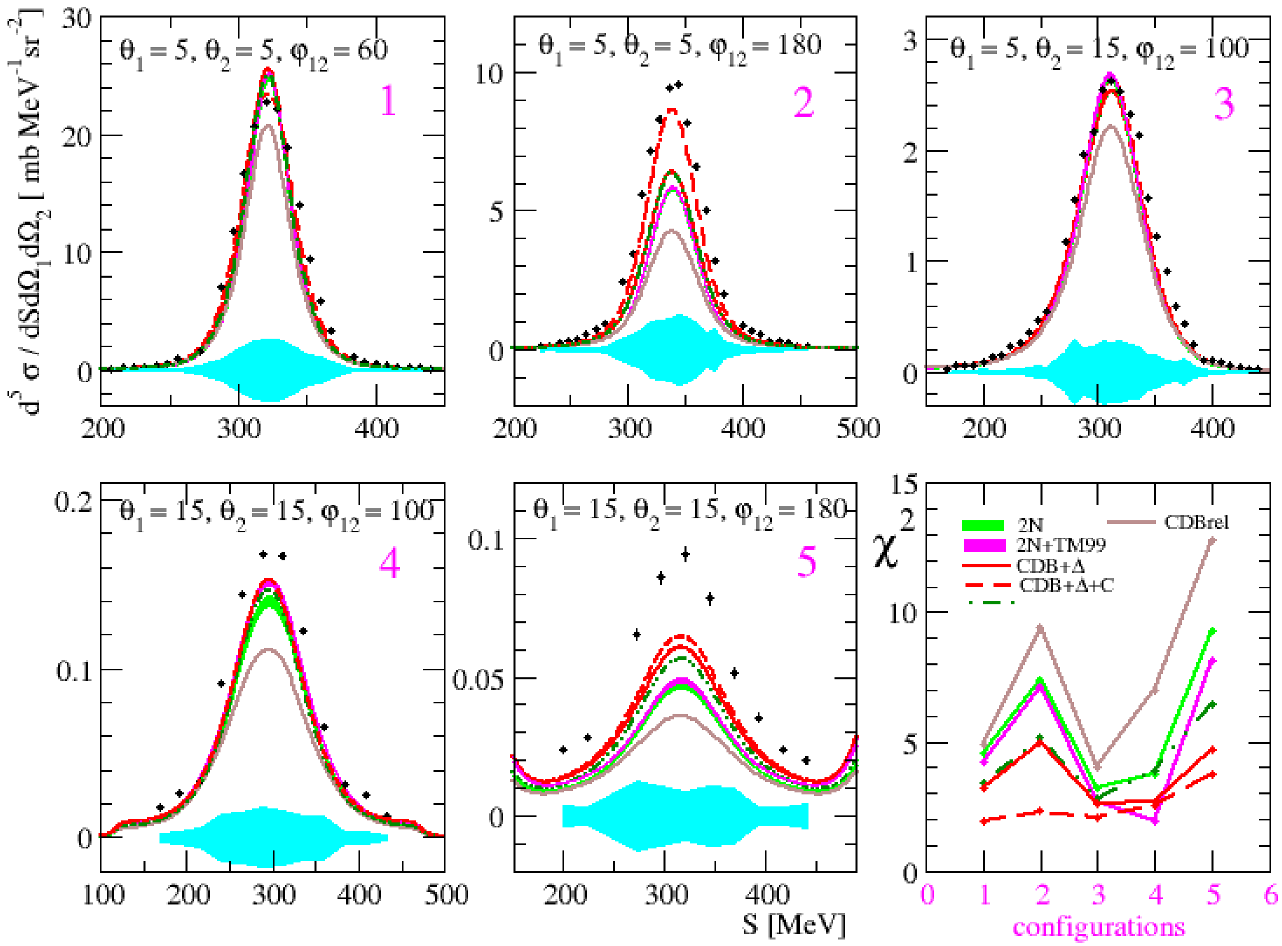
$$\chi^2 = \frac{1}{n_{d.o.f.}} \sum \frac{(\sigma_{theo}(\xi) - \sigma_{\exp}(\xi))^2}{(\Delta\sigma_{stat}(\xi) + \Delta\sigma_{sys}(\xi))^2}$$

$\zeta = (\theta_1, \theta_2, \varphi_{12}, S)$ set of kinematic variables

$\Delta\sigma_{stat}, \Delta\sigma_{sys}$ statistical and systematical uncertainties

$\sigma_{\exp}, \sigma_{theo}$ cross section data and various calculations

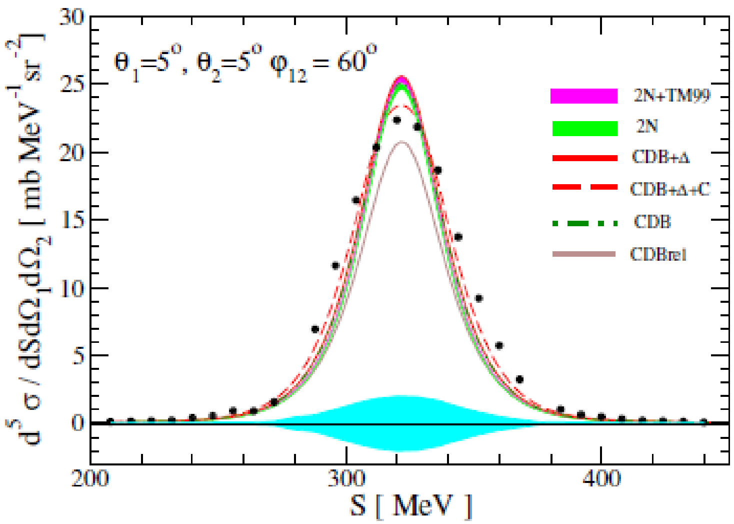
$n_{d.o.f}$ number of data points

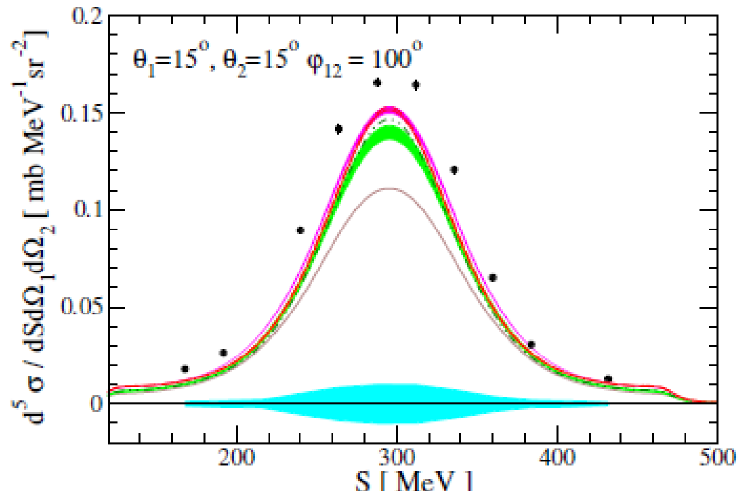


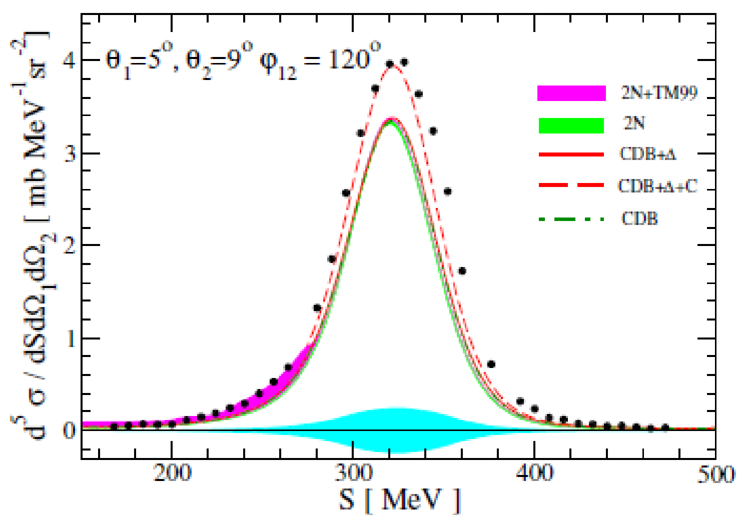
Predicted relativistic effects reduce cross section values in this region.

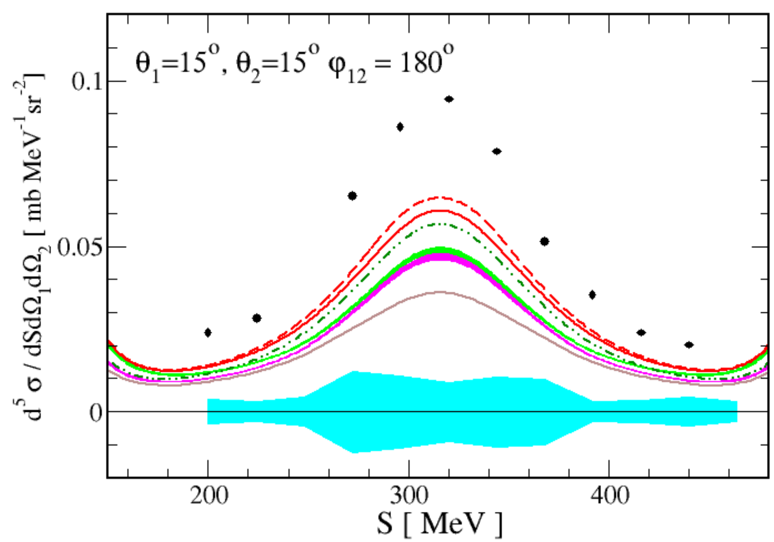
Barbara Kłos for Wasa-at-Cosy Collaboration, University of Silesia

Differential cross section (340 MeV) Specific examples









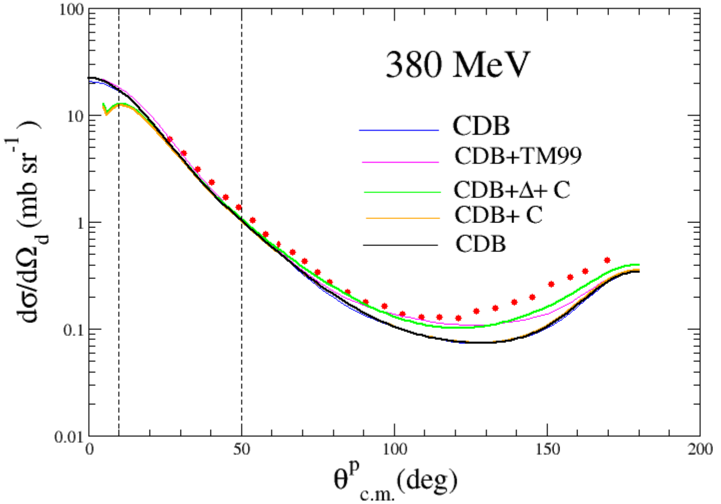
Coulomb force plays important role

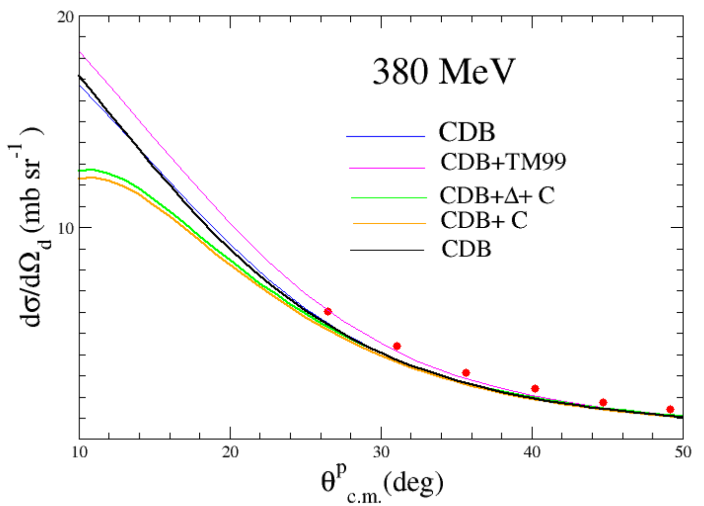
Missing large 3NF contributions ?
Relativistic effects in 3NF?
To be verified at the higher energy

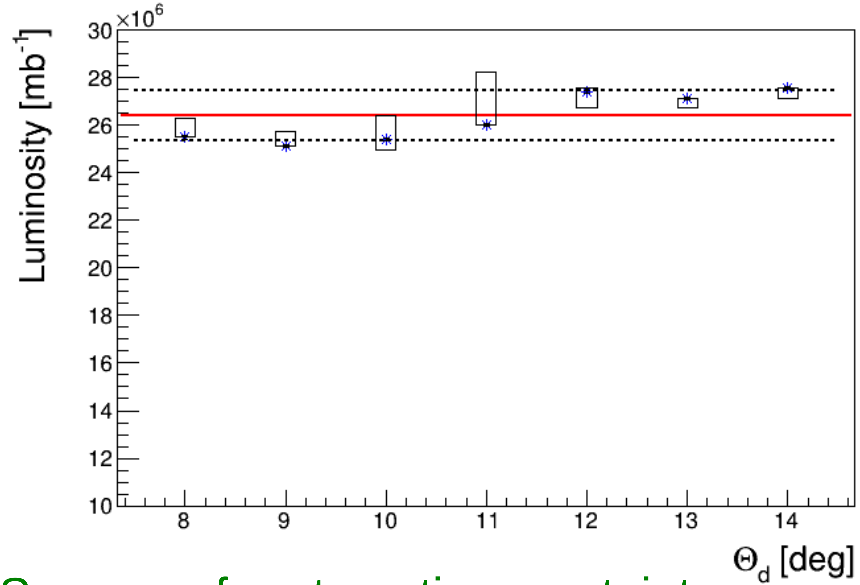
Barbara Kłos for Wasa-at-Cosy Collaboration,
University of Silesia

Data Analysis (380 MeV)

Luminosity

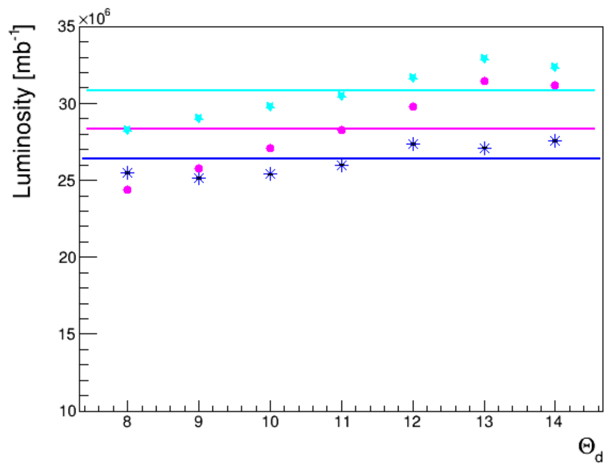






Sources of systematic uncertainty:

- range of data integration



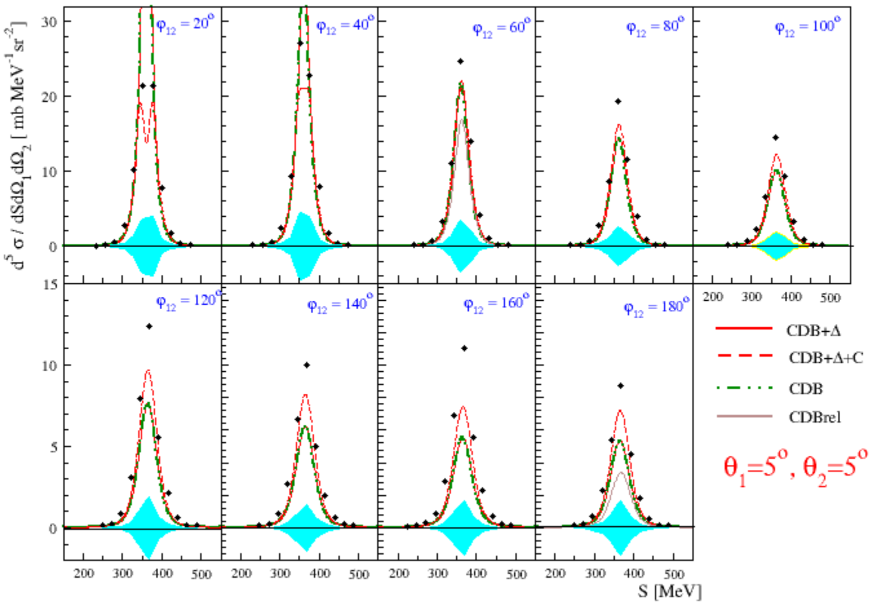
Source of normalization

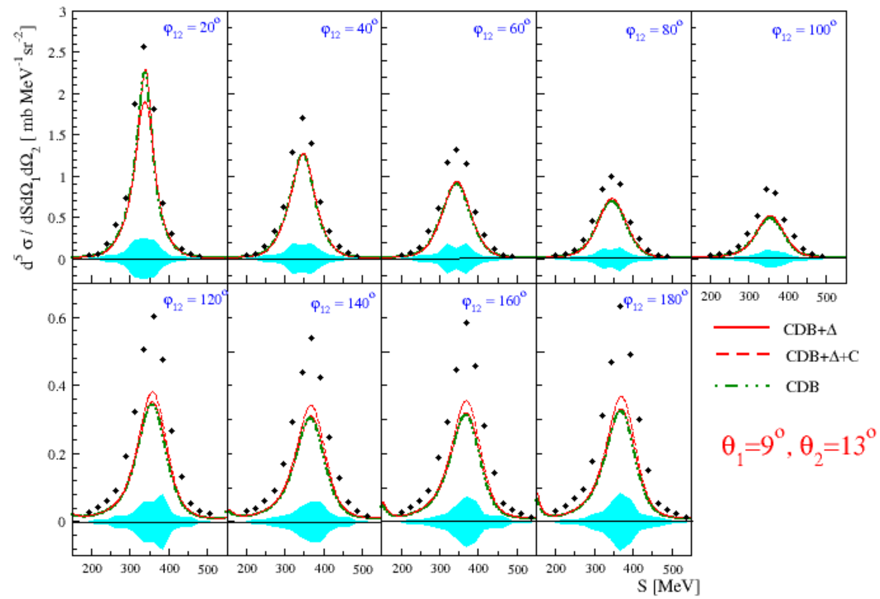
- experiment
- CDB+TM99
- CDB+Δ+C
- $2.640 \times 10^{7} mb^{-1}$
- $2.836 \times 10^{7} mb^{-1}$
- $3.081 \times 10^{7} mb^{-1}$

Barbara Kłos for Wasa-at-Cosy Collaboration,
University of Silesia

● (experimental points) K. Ermisch *et al.*, Phys. Rev. C **68**, 051001(R) (2003).

Differential cross sections at 380 MeV





In all the 189 studied configurations, data points are systematically above all the theories. Most likely, we are observing a normalization problem.

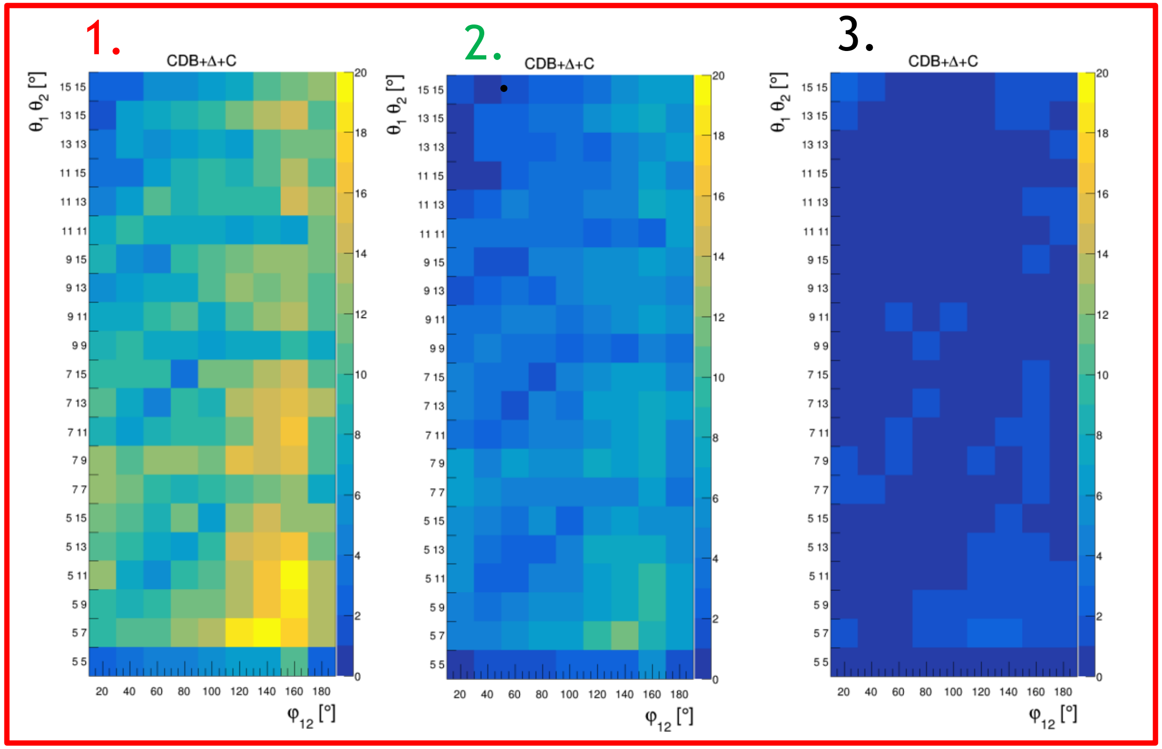
This problem is investigated in two ways:

- luminosity is obtained on the basis of elastic scattering cross section calculated in the CDB+Δ+C approach;
- common correction factor is introduced to provide the best agreement of the data with the CDB+Δ+C calculations for the breakup reaction.

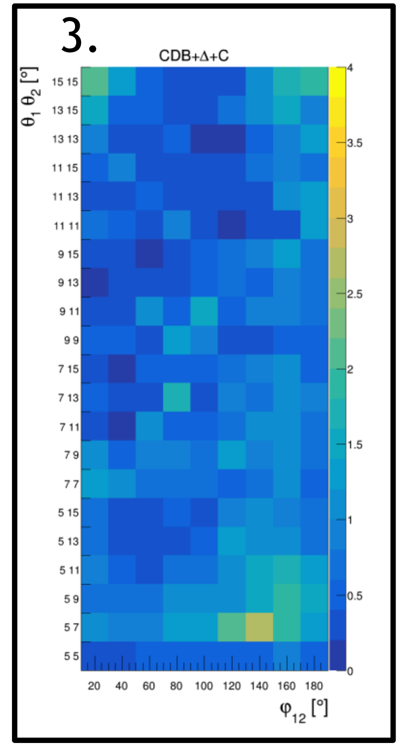
Barbara Kłos for Wasa-at-Cosy Collaboration,
University of Silesia

Chi-squared analysis (380 MeV)

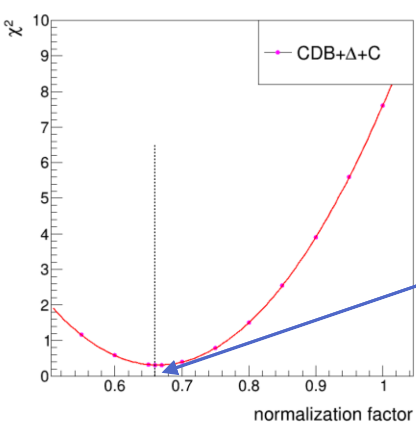
the same scale



the different scale



The χ^2 results obtained for all angular configuration separately in a logarithmic scale for theoretical model CDB+Δ+C (Deltuva).



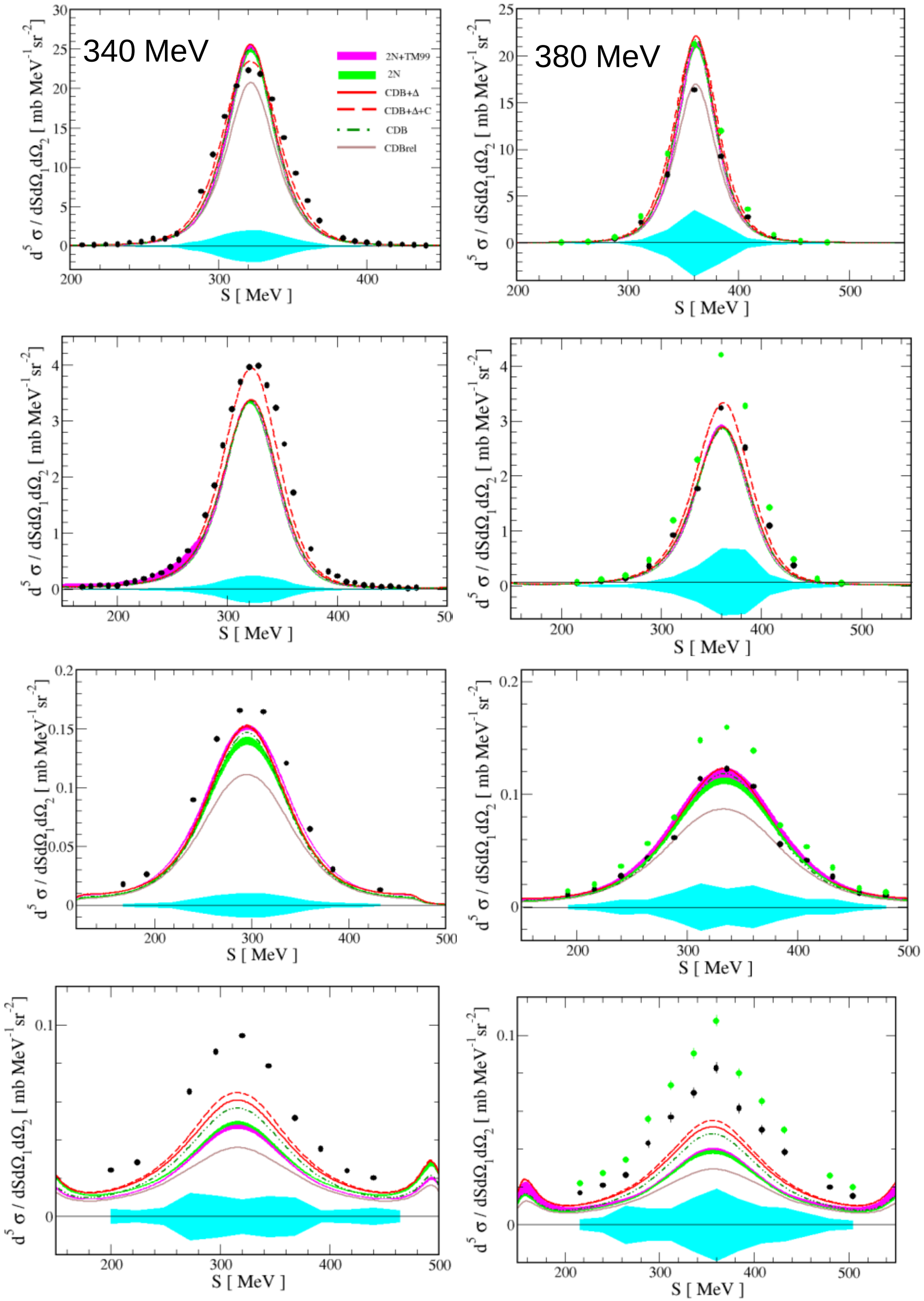
luminosity is obtained on the basis of elastic scattering cross section

1. experiment (Ermisch)
2. calculated in the CDB+Δ+C approach

3 The best global χ^2 obtained for a factor of 0.66

Barbara Kłos for Wasa-at-Cosy Collaboration,
University of Silesia

Specific examples (comparison between energies)



Θ_1=5°, θ_2=5°, φ_{12}=60°

Θ_1=5°, θ_2=9°, φ_{12}=120°

Θ_1=15°, θ_2=15°, φ_{12}=100°

Θ_1=15°, θ_2=15°, φ_{12}=180°

Experimental data for 380 MeV

- normalized to theory
- corrected by 0.66

Barbara Kłos for Wasa-at-Cosy Collaboration,
University of Silesia

Results (340 and 380 MeV, Forward Detector)

- Coulomb force plays an important role (the lowest effect is observed at $\varphi_{12} = 100^{o}$),
- the 3NF effects are predicted to be small at forward angles,
- at certain configurations, in particular $\theta_1 = 5^{o}$, $\theta_2 = 5^{o}$, $\varphi_{12} = 60^{o}$, an interplay of 3NF effects, Coulomb force and relativistic effects can be observed (at 340 MeV),
- at $\theta \geq 13^{o}$ and/or $\varphi_{12} \geq 140^{o}$ all the calculations systematically underestimate the experimental data. The discrepancy is even increased by relativistic calculations. Is it due to missing large 3NF contribution?

Study of Three-Nucleon Dynamics in the dp breakup collisions using the WASA detector at COSY-Jülich

University of Silesia, Katowice, Poland

Jagiellonian University, Kraków, Poland

University of Warsaw , Warszawa, Poland

Institute of Nuclear Physics PAN, Kraków, Poland

Forschungszentrum Juelich, Germany

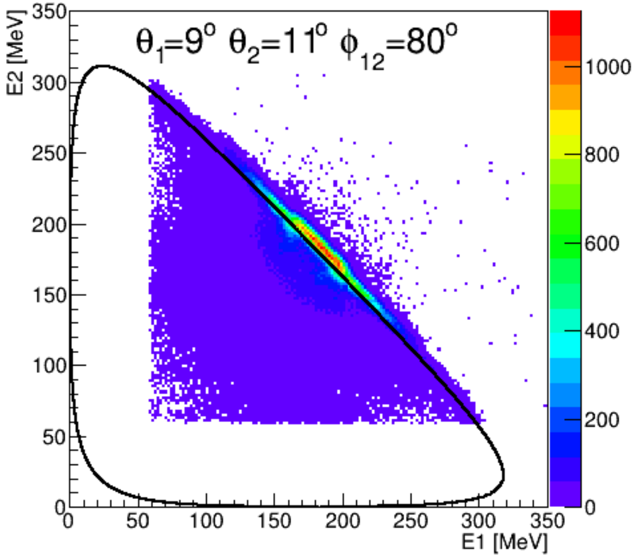
WASA@COSY Collaboration

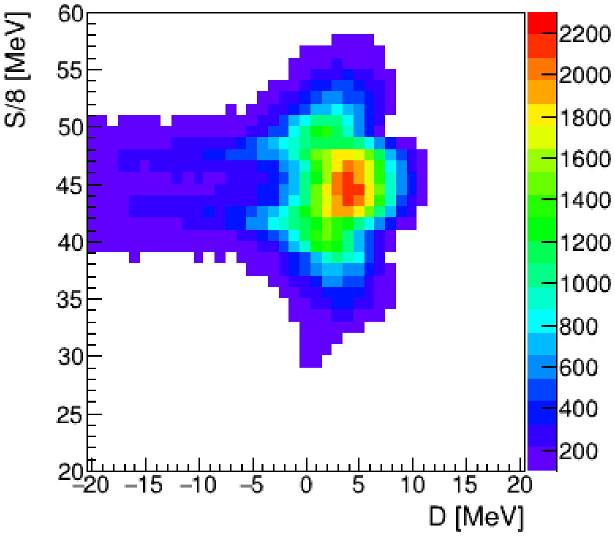
THANK YOU

Barbara Kłos for Wasa-at-Cosy Collaboration,
University of Silesia

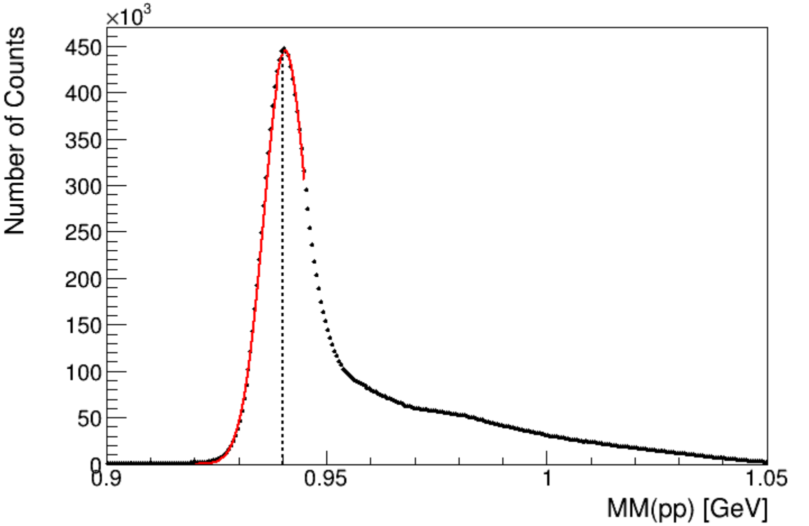
Data Analysis (380MeV)

Selection of events and background subtraction



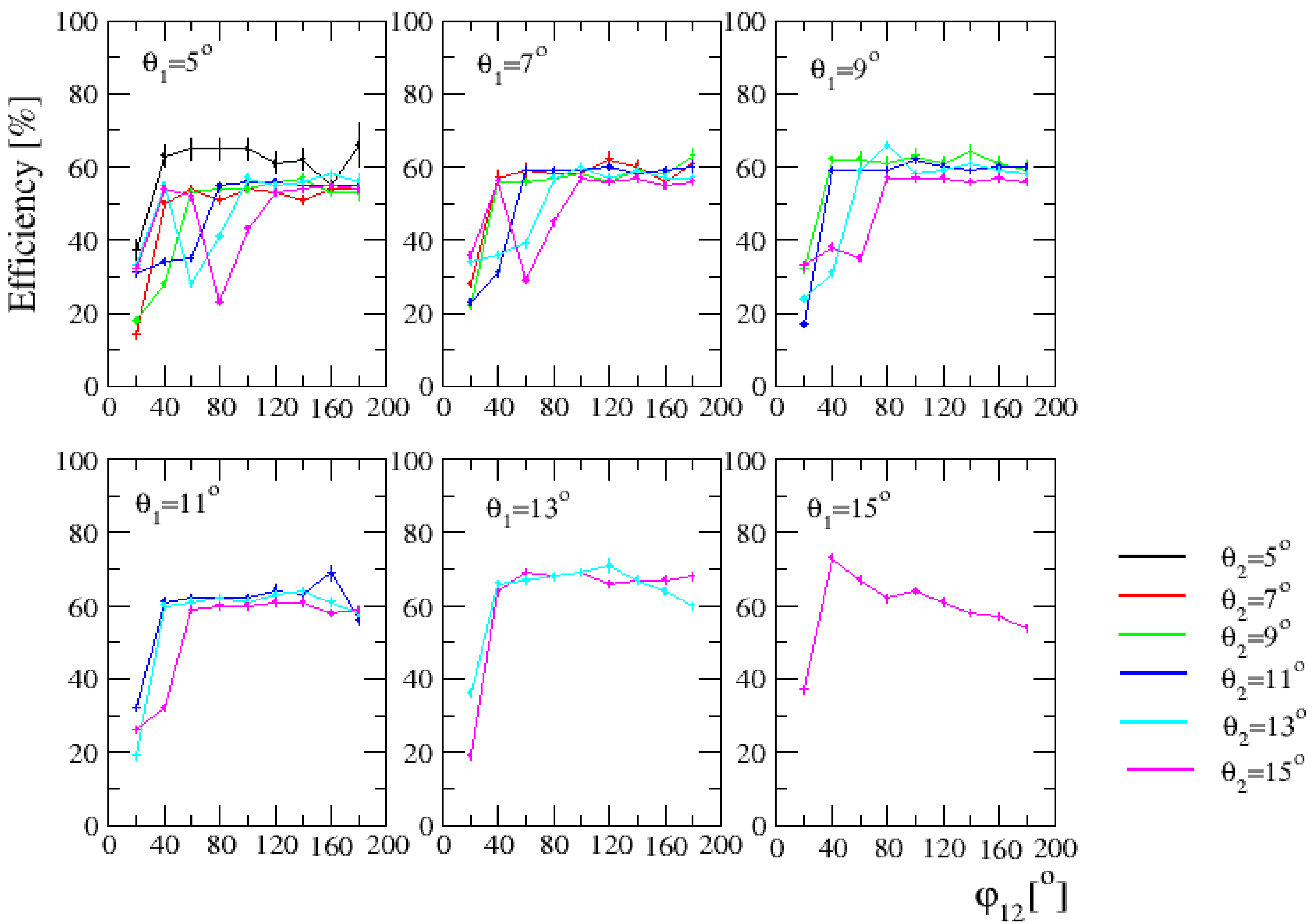


Missing mass



Data Analysis (380 MeV)

Efficiency of the detection system for proton-proton coincidences obtained for each kinematical configuration ($\theta_1,\theta_2, \varphi_{12}$) using MC

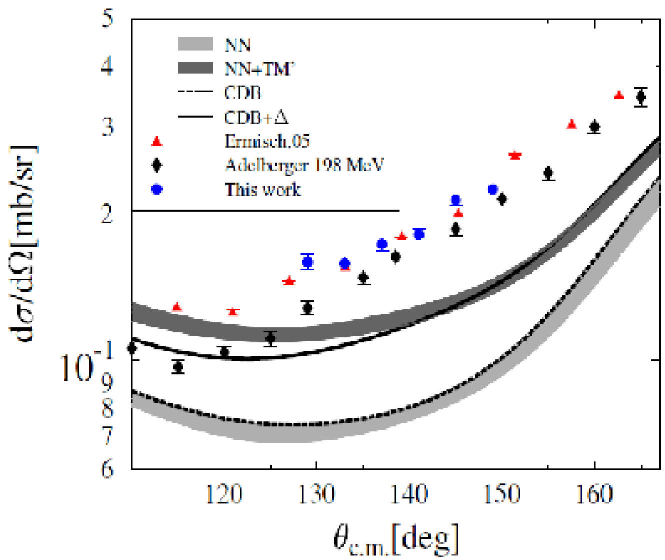


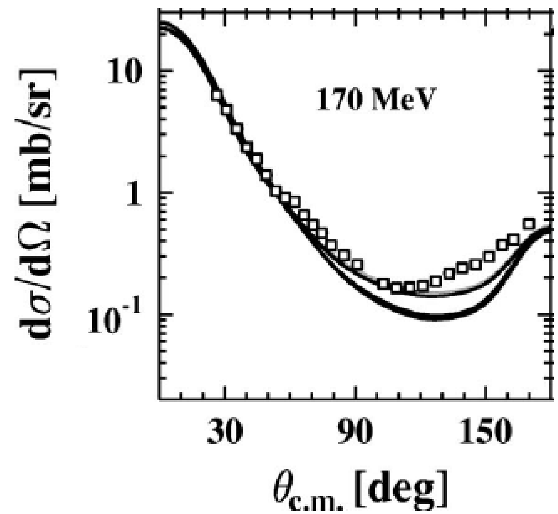
General information of d-p experiment @Wasa

deuteron beam energy	300, 340, 380, 400 MeV
reaction channels	dp → dp dp → ppn dp → ^{3}He + γ dp → dp γ
luminosity	~10^{29}/s/cm^2
deuterons in flat top	(1.3-1.4)*10^8
total trigger rate	~6*10^4 events/s (trigger in) ~3*10^4 events/s (trigger out)
coincidence rate per bin	0.05-0.1 breakup events/s
Δσ /σ	~1%
collected data	22 TB (984 runs ,~22GB per run)

Barbara Kłos for Wasa-at-Cosy Collaboration,
University of Silesia

Elastic scattering data for cross sections normalization

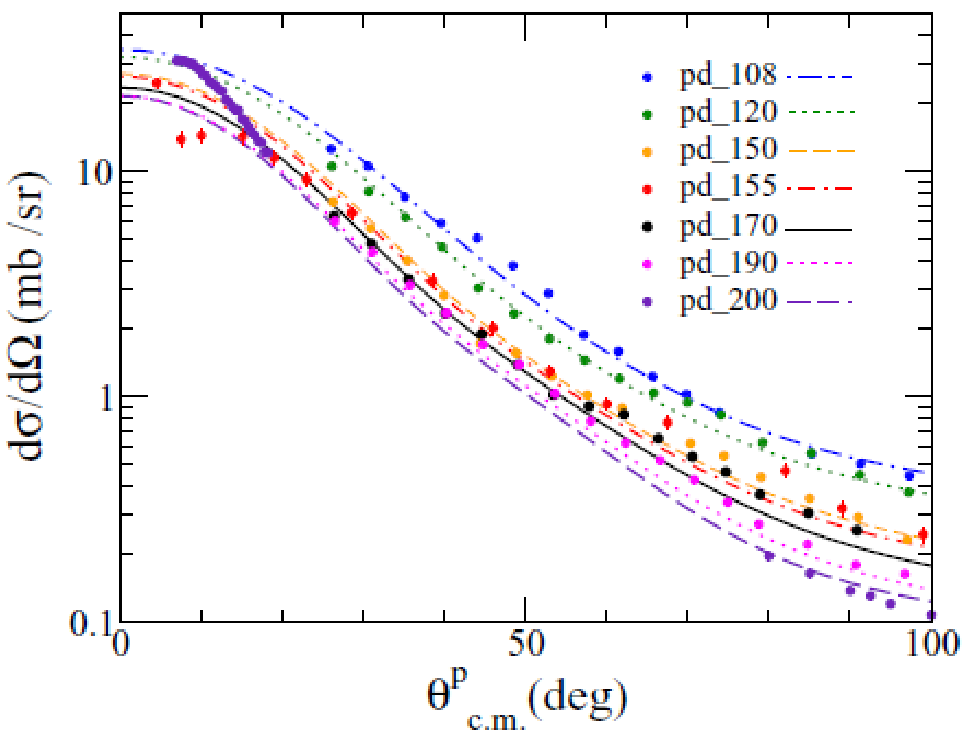




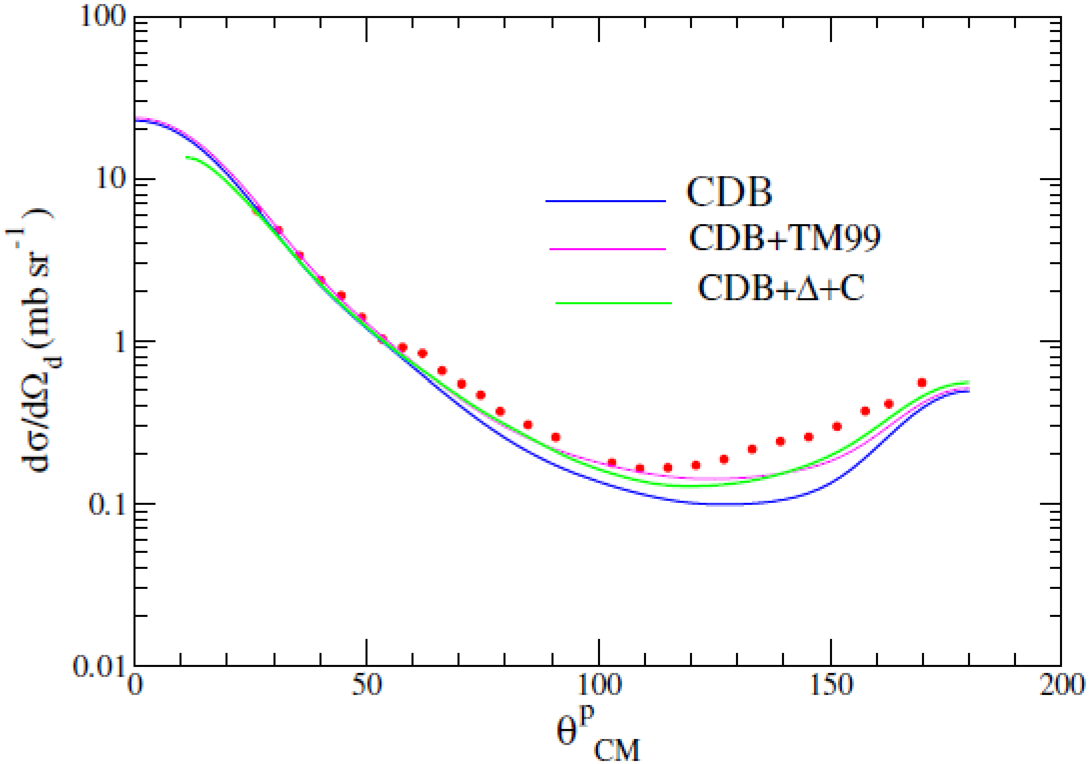
elastic p+d:
@198 MeV (Adelberger)
stat.err.~3%
@170, @190 MeV
(Ermish, Mardanpour)
stat.err. ~3%
syst.err.~ 7%

K. Ermish, Phys. Rev. C 68, 051001, (2003)
R.E. Adelberger, Phys. Rev. D 5, 2139 (1972)
H. Mardanpour, Ph.D. Thesis, 2008

Cross section data & calculations for elastic scattering at the energies near 340 MeV (170MeV/nucleon)

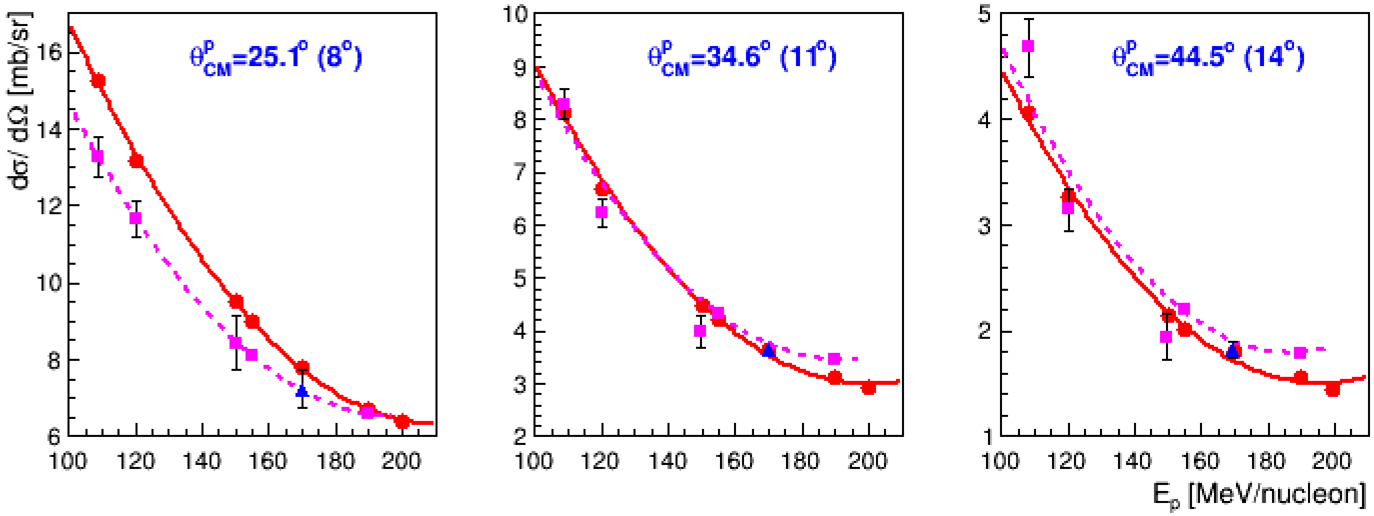


Experimental differential cross section of the reaction $^{2}H(p,dp)$ in the center of mass (CM) system in angular range of FD, at the incident-beam energies: 108, 120, 150, 170, 190 MeV [Erm03], 155 MeV [Kur64] and 200 MeV [Ade72, Roh98] Tje lines show the result of the theoretical calculations with th CD Bonn potential and the TM99 3NF



Angular distribution of the elastic scattering cross section in the CM system. Red dots represent the measured cross-section values for elastic scattering at 170 MeV([Erm03]). The solid lines show the results of the theoretical calculations with the CDBonn potential and the TM99 3NF as well as coupled-channel calculation with CD Bonn+Δ and Coulomb force included (CDB+Δ+C).

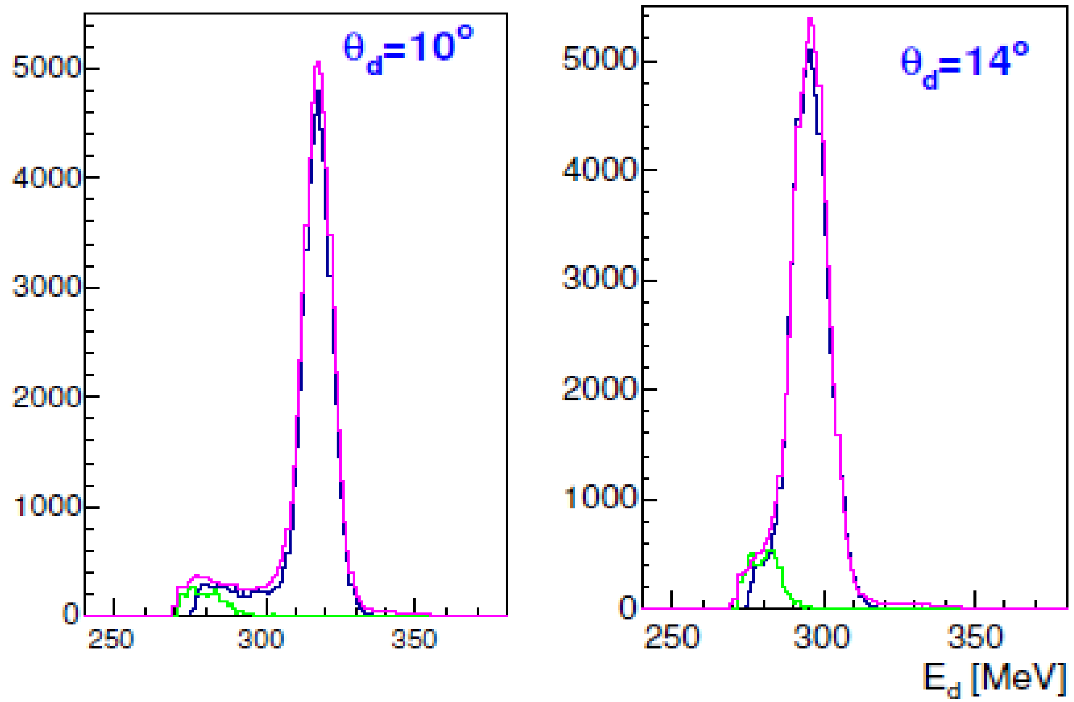
Determination of luminosity



Experimental and theoretical energy dependence of the elastic scattering cross section a given Θ^p_{CM} angle in the CM system in a function of incident beam energy . The solid and dashed lines present functions fitted to points obtained from theoretical calculations and the data, respectively. Triangle and squares were determined from pd elastic scattering experiments,

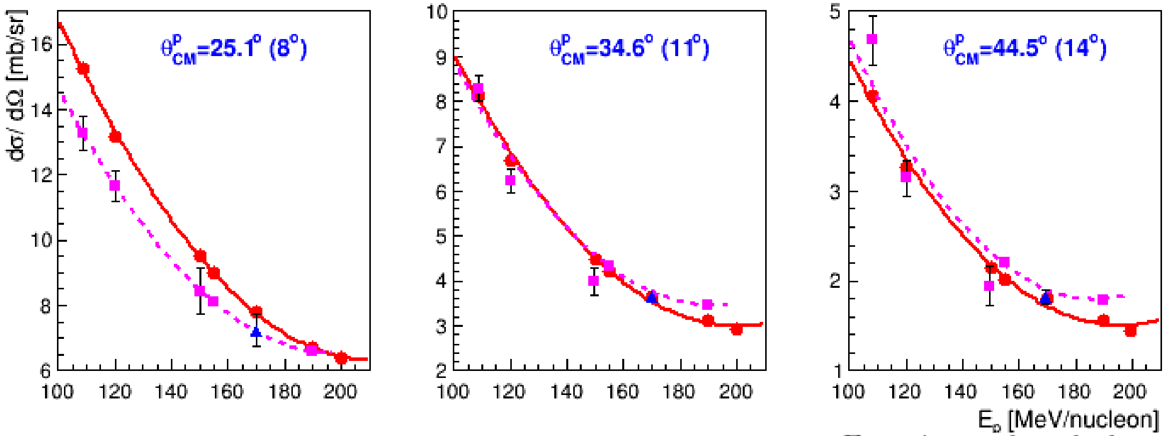
Selection of elastic scattering events

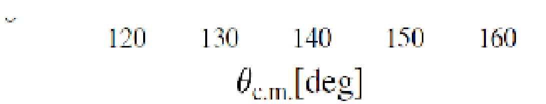
Contribution of proton background



Energy spectra of elastically scattered deuterons registred for the chosen angles. The experimental data are compared to MC simulation. The green represents protons „leeking through" the deuterons cuts in the MC simulation of the dp breakup reaction. The lines are arbitrary normalized

Elastic scattering data for cross sections normalization

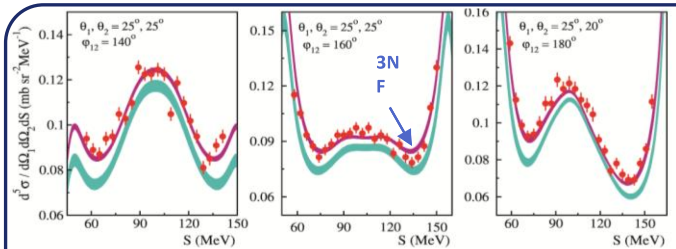


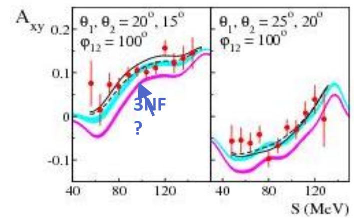


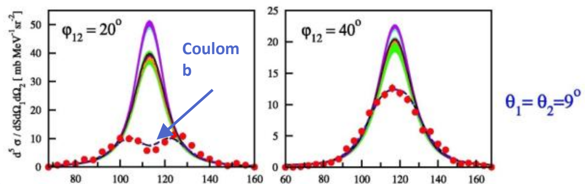
Experimental and theoretical energy dependence of the elastic scattering cross section a given Θ^{p}_{CM} angle in the CM system in a function of incident beam energy . The solid and dashed lines present functions fitted to points obtained from theoretical calculations and the data, respectively. Triangle and squares were determined from pd elastic scattering experiments.

elastic p+d:
@198 MeV (Adelberger)
stat.err.~3%
@170, @190 MeV
(Ermish, Mardanpour)
stat.err. ~3%
syst.err.~ 7%

K. Ermish, Phys. Rev. C 68, 051001, (2003)
R.E. Adelberger, Phys. Rev. D 5, 2139 (1972)
H. Mardanpour, Ph.D. Thesis, 2008

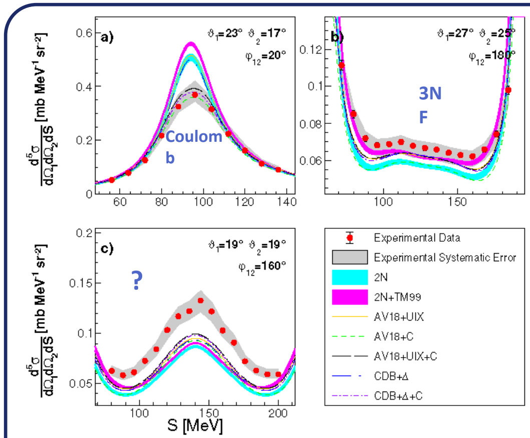






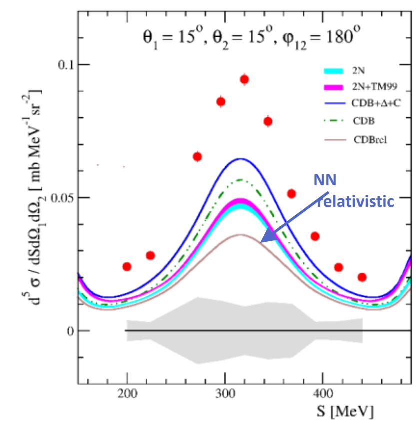
St.Kistryn et al., Phys. Rev C 72 , 044006 (2005)
E.Stephan et al., Phys. Rev C 82 , 014003 (2010)
I.Ciepał et al., Few-Body Syst. 56, 665 (2015)

65 MeV/nucleon



W. Parol et al., Phys. Rev C 102 , 054002 (2020)

80 MeV/nucleon



B.Kłos WASA@COSY, Phys. Rev C 101 , 044001 (2020)

170 MeV/nucleon

H. Witała et al.: 2N, 2N+TM99, CDBrel
A.Deltuva et al.: CBD+Δ+C, CBD+Δ+C,AV18, AV18+UIX, AV18+C, AV18+UIX+C